



Interference between W' and W in single-top quark production processes

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Abstract

The Letter is devoted to studies of prospects to search for hypothetical W' gauge bosons at hadron colliders via single-top quark production process. A special attention is paid to the interference between the Standard Model (SM) W and W' boson contributions. A model independent analysis is performed for a wide interval of W' masses potentially acceptable for a detection at the Tevatron and LHC. It is shown that the interference contribution to the cross section of the most promising s -channel single-top production mode could be as large as 30% for certain parameter points which is comparable to NLO effects computed in previous studies separately for the W' signal and the SM single-top background. The interference contribution affects particle distributions and has to be taken into account for more accurate W' signal and background simulation.

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1. Introduction

The interactions of charged weak currents are realized in SM via exchange of charged massive gauge boson fields W^+ and W^- . Although any additional charged massive bosons are not found yet experimentally their existence is predicted by various extensions of SM. The wide-common name for this vector boson field is W' . Such models like Non-Commuting Extended Technicolor [1], Composite [2,3] and Little Higgs models [4–6], models of composite gauge bosons [7], Supersymmetric top-flavor models [8], Grand Unification [9] and Superstring theories [10–12] represent examples where extension of gauge group lead to appearing of W' . Physical properties and interaction parameters of W' can vary from model to model. For example the W' is presented in models of Universal extra-dimensions [13,14] as the lowest Kaluza–Klein mode of charged gauge boson W^\pm and has the same (V-A) chiral structure of interaction to fermion fields as the SM W^\pm . But in top-flavor models the W' boson interacts differently with fermions of the first two and third generations. It depends on magnitude of gauge coupling parameters g_h and g_l . If $g_h > g_l$ the W' couples stronger to the third generation and weaker to the first two

generations, and vice versa if $g_h < g_l$ [15,16]. Frequently W' bosons are discussed in connection with so-called Left–Right symmetric models [17–23]. The simplest extension of SM with Left–Right symmetry is based on $U(1) \times SU(2)_L \times SU(2)_R$ gauge group. The left-handed fermions transform as doublets under $SU(2)_L$ and invariant under $SU(2)_R$ contrary to the right-handed ones which transform as doublets under $SU(2)_R$ and invariant under $SU(2)_L$. Linear combinations of charged gauge fields produce massive eigenstates: $W_1 = \cos \zeta W_L + \sin \zeta W_R$, $W_2 = -\sin \zeta W_L + \cos \zeta W_R$, where W_1 is identified as observed W boson, and W_2 as a new W' boson, ζ is a mixing parameter between bosons for the right and left gauge groups. Parameter ζ is constrained to a very small value ($\zeta < 10^{-3}$) to suppress (V + A) charged currents for light SM fermions in accord with experimental data [24,25]. In this case interactions of W' with fermions becomes almost purely right-handed. In Left–Right symmetric models the parity is broken spontaneously which leads to different masses for the $SU(2)_L$ and $SU(2)_R$ gauge bosons. There are two well-known variants of Left–Right models called *manifest* and *pseudo-manifest* for which the Cabibbo–Kobayashi–Maskawa matrices $V^L = V^R$ and $V^L = V^{R*}$ respectively.

Although the W' is not discovered yet there are experimental limits on its mass. Various models with W' contain many parameters, and indirect constraints of W' are highly model dependent. Indirect searches for W' being extracted from leptonic

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and semileptonic decays and also from cosmological and astrophysical data give very wide range for upper limits on W' mass varying from 549 GeV up to 23 TeV [26].

The direct limits on W' masses are based on hypothesis of purely right or left-handed interacting W' with SM-like coupling constants. The limits from direct searches in leptonic decay modes of W' depend on a mass of a hypothetical right-handed neutrino. In case $M_{W'} < M_{\nu_R}$ the decay mode $W_R \rightarrow \nu_R, l$ is not kinematically allowed. The limits in this case have been extracted from light jet decay mode being $M_{W'} > 800$ GeV [27]. In case $M_{W'} > M_{\nu_R}$ the decay of W' to ν_R and l is allowed, and the limit $M_{W'} > 786$ GeV [28] has been obtained in this case from the leptonic decay modes combining both electron and muon channels.

One of the most promising and perspective way to search for W' is studying decays of W' to quarks of the third generation ($W' \rightarrow t\bar{b}$). This channel has relatively small QCD background comparing to light jet channel, and it is less model dependent. Searches in this channel at the Tevatron give a limit on W' mass $M_{W'} > 536$ GeV at 95% CL in assumption $M_{W'} > M_{\nu_R}$. The assumption $M_{W'} < M_{\nu_R}$ leads to slightly better limit $M_{W'} > 566$ GeV [29] due to absence of the decay to ν_R and correspondingly larger decay Br fraction to $t\bar{b}$. The W' boson decaying to the top and bottom quarks contribute to the single-top production process. The single-top production being interesting itself for various aspects of the top quark physics gives perspective channel to search for W' [30]. In consequence that both W and W' contribute to single-top production process and have the couplings with the same fermion multiplets they should interfere to each other [31]. It should be noted that the interference becomes possible only for the left-handed interacting W' component because the SM W interacts only with left-handed electroweak currents being orthogonal to the right-handed interactions.

The aim of this Letter is to study in more detail the interference phenomena between the SM W and the W' bosons in the single-top production process at the Tevatron and LHC energies.

Our Letter is organized as follows. In Section 2 we present a simple analytical formula and a short analysis of the interference contribution. Section 3 describes the results of numerical calculations. In the last section the summary and conclusion are given.

2. Interference between W' and W

To consider the W' production in a model independent way we write down the lowest dimension effective Lagrangian of W' interactions to quarks in most general form (possible higher dimension effective operators are not taken into account in our analysis):

$$\mathcal{L} = \frac{V_{q_i q_j}}{2\sqrt{2}} g_w \bar{q}_i \gamma_\mu (a_{q_i q_j}^R (1 + \gamma^5) + a_{q_i q_j}^L (1 - \gamma^5)) W'_{q_j} + \text{H.c.} \quad (1)$$

where $a_{q_i q_j}^R, a_{q_i q_j}^L$ —left and right couplings of W' to quarks, $g_w = e/(s_w)$ is the SM weak coupling constant and $V_{q_i q_j}$ is the SM CKM matrix element. The notations are taken such that for so-called SM-like W' $a_{q_i q_j}^L = 1$ and $a_{q_i q_j}^R = 0$.

As was mentioned a promising way to search for W' is the single-top quark production processes. There are three kinematically-different single-top production channels at hadron colliders, namely, s -channel, t -channel and associated Wt channel. However for large W' mass region, which we are interested in, the W' contribution to the t - and associated Wt channels becomes too small to be detectable, and the only s -channel where W' may contribute as a resonance remains important.

For the leading s -channel subprocess $u\bar{d} \rightarrow t\bar{b}$ the matrix element squared has the following form:

$$|M|^2 = V_{tb}^2 V_{ud}^2 (g_w)^4 \left[\frac{(p_u p_b)(p_d p_t)}{(\hat{s} - m_W^2)^2 + \gamma_W^2 m_W^2} + 2a_{ud}^L a_{tb}^L (p_u p_b)(p_d p_t) \times \frac{(\hat{s} - m_W^2)(\hat{s} - M_{W'}^2) + \gamma_{W'}^2 \Gamma_{W'}^2}{((\hat{s} - m_W^2)^2 + \gamma_W^2 m_W^2)((\hat{s} - M_{W'}^2)^2 + \gamma_{W'}^2 M_{W'}^2)} + \frac{(a_{ud}^L)^2 (a_{tb}^L)^2 + a_{ud}^R{}^2 a_{tb}^R{}^2}{(\hat{s} - M_{W'}^2)^2 + \Gamma_{W'}^2 M_{W'}^2} (p_u p_b)(p_d p_t) + \frac{(a_{ud}^L)^2 a_{tb}^R{}^2 + a_{ud}^R{}^2 (a_{tb}^L)^2}{(\hat{s} - M_{W'}^2)^2 + \Gamma_{W'}^2 M_{W'}^2} (p_u p_t)(p_d p_b) \right] \quad (2)$$

where a_{ud}^L, a_{ud}^R —left and right couplings of W' to u, d quarks, and a_{tb}^L, a_{tb}^R —left and right couplings of W' to t, b quarks.

One can rewrite the formula in terms of Mandelstam variables using $(p_u p_b) = -\hat{t}/2$, $(p_d p_t) = (M_t^2 - \hat{t})/2$, $(p_d p_b) = -\hat{u}/2$, $(p_u p_t) = (M_t^2 - \hat{u})/2$. In these notations the formula reads as follows

$$|M|^2 = V_{tb}^2 V_{ud}^2 (g_w)^4 \left[\frac{\hat{t}(\hat{t} - M_t^2)}{(\hat{s} - m_W^2)^2 + \gamma_W^2 m_W^2} + 2a_{ud}^L a_{tb}^L \hat{t}(\hat{t} - M_t^2) \times \frac{(\hat{s} - m_W^2)(\hat{s} - M_{W'}^2) + \gamma_{W'}^2 \Gamma_{W'}^2}{((\hat{s} - m_W^2)^2 + \gamma_W^2 m_W^2)((\hat{s} - M_{W'}^2)^2 + \gamma_{W'}^2 M_{W'}^2)} + \frac{(a_{ud}^L)^2 (a_{tb}^L)^2 + a_{ud}^R{}^2 a_{tb}^R{}^2}{(\hat{s} - M_{W'}^2)^2 + \Gamma_{W'}^2 M_{W'}^2} \hat{t}(\hat{t} - M_t^2) + \frac{(a_{ud}^L)^2 a_{tb}^R{}^2 + a_{ud}^R{}^2 (a_{tb}^L)^2}{(\hat{s} - M_{W'}^2)^2 + \Gamma_{W'}^2 M_{W'}^2} \hat{u}(\hat{u} - M_t^2) \right] \quad (3)$$

in complete agreement for the SM part (first term) with [32] and for W' part (last two terms) with the result from the paper [33].

The case of the SM-like W' corresponds to the couplings $a_{ud}^L = a_{tb}^L = 1$ and $a_{ud}^R = a_{tb}^R = 0$.

One should stress that the interference (second) term is proportional to the left couplings only because the SM W -boson has the only left ($V - A$) type of the interaction. The term containing the product of widths $\gamma_W^2 \Gamma_{W'}^2$ is completely negligible comparing to $(\hat{s} - m_W^2)(\hat{s} - M_{W'}^2)$ for any values of \hat{s} somewhere in the region between the W and W' boson masses, and it

makes the interference term very small if \hat{s} is very close (equal) to one of the masses. However, in general, the interference term is not small being negative in the region of $M_W^2 < \hat{s} < M_{W'}^2$ and positive for $\hat{s} > M_{W'}^2$ (if the constants a_L are positive). The interference term depends very weakly on the total width $\Gamma_{W'}$ of W' boson. As shown in the next section the interference contribution could be rather large and should be taken into account for a signal and background simulations in searches for W' if the W' has left-handed component in its interaction to fermions.

Note that we assume here the couplings $a_{ud}^L, a_{ud}^R, a_{tb}^L, a_{tb}^R$ to be real. Generalization of the formula to the complex couplings is straightforward and not given here.

After the integration over the \hat{t} -variable the partonic cross section takes the form:

$$\begin{aligned} \hat{\sigma}(\hat{s}) = & \frac{\pi \alpha_W^2}{6} V_{tb}^2 V_{ud}^2 \frac{(\hat{s} - M_t^2)^2 (2\hat{s} + M_t^2)}{\hat{s}^2} \\ & \times \left[\frac{1}{(\hat{s} - m_W^2)^2 + \gamma_W^2 m_W^2} + 2a_{ud}^L a_{tb}^L \right. \\ & \times \frac{(\hat{s} - m_W^2)(\hat{s} - M_{W'}^2) + \gamma_W^2 \Gamma_{W'}^2}{((\hat{s} - m_W^2)^2 + \gamma_W^2 m_W^2)((\hat{s} - M_{W'}^2)^2 + \Gamma_{W'}^2 M_{W'}^2)} \\ & \left. + \frac{(a_{ud}^L a_{tb}^L + a_{ud}^R a_{tb}^R + a_{ud}^L a_{tb}^R + a_{ud}^R a_{tb}^L)}{(\hat{s} - M_{W'}^2)^2 + \Gamma_{W'}^2 M_{W'}^2} \right] \quad (4) \end{aligned}$$

where $\alpha_W = g_W^2/(4\pi)$ and $\hat{s} = x_u x_d s$. The well-known SM cross section (first term) completely agrees with [34].

3. Numerical illustrations

Numerical computations and Monte Carlo simulations have been performed for the Tevatron and LHC energies $\sqrt{s} = 1.96$ and 14 TeV. Top quark mass was chosen $M_t = 175$ GeV. Results are given for six different sets of W' masses from 0.5 up to 1 TeV (for Tevatron) and from 0.6 up to 5 TeV (for LHC) separately for both pure right and left-handed interacting W' . Partonic distribution functions CTEQ611 have been used. The QCD scale has been set to $M_{W'}$. The couplings of W' to SM-fields have been implemented into CompHEP [35] which was used to compute the W' width (see Table 1), production cross sections, kinematical distributions and to generate unweighted events for different sets of W' masses. For the case of left-handed interacting W' we set $a_{ud}^L = a_{tb}^L = 1$, $a_{ud}^R = a_{tb}^R = 0$, for the right-handed case $a_{ud}^L = a_{tb}^L = 0$, $a_{ud}^R = a_{tb}^R = 1$ and for SM all the parameters are equal to zero $a_{ud}^L = a_{tb}^L = a_{ud}^R = a_{tb}^R = 0$.

We simulate the process $p\bar{p}(pp) \rightarrow W/W' \rightarrow t\bar{b}$ which includes 8 subprocesses with different parton combinations in the initial states.

Table 1

The total width (GeV) of the W' in dependence on W' mass (GeV) for the top quark mass $M_t = 175$ GeV assuming that decays to both quarks and leptons are allowed (if W' decays to leptons are not allowed the widths will be smaller by a factor about 3/4)

$M_{W'}$	500	600	700	800	900	1000
$\Gamma_{W'}$	16.14	19.65	23.12	26.58	30.01	33.44

Table 2

Total cross section of the process $p\bar{p} \rightarrow W/W' \rightarrow t\bar{b}$; contribution of the interference term (IT, in %) and contribution of leading $u\bar{d} \rightarrow W/W' \rightarrow t\bar{b}$ subprocess to the total cross section for various W' masses and Tevatron energy ($\sqrt{s} = 1960$ GeV). Interference term is zero for the right interacting W'

$M_{W'}$ GeV	SM + left W'			SM + right W'	
	σ_{tot} , pb	IT, %	$\sigma_{u\bar{d} \rightarrow t\bar{b}}$, %	σ_{tot} , pb	$\sigma_{u\bar{d} \rightarrow t\bar{b}}$, %
500	2.13	12.4	99.0	2.39	98.8
600	0.846	21.2	98.9	1.02	98.7
700	0.403	30.8	98.2	0.524	98.1
800	0.256	33.4	97.3	0.341	97.4
900	0.212	30.5	96.6	0.275	96.8
1000	0.202	23.5	96.4	0.25	96.6

Table 3

Total cross section of the process $pp \rightarrow W/W' \rightarrow t\bar{b}$, contribution of the interference term (IT, in %) and contribution of leading $u\bar{d}(\bar{d}u) \rightarrow W/W' \rightarrow t\bar{b}$ subprocess to the total cross section for various W' masses and LHC energy ($\sqrt{s} = 14$ TeV). Interference term is zero for the right interacting W'

$M_{W'}$ GeV	SM + left W'			SM + right W'	
	σ_{tot} , pb	IT, %	$\sigma_{u\bar{d}(\bar{d}u) \rightarrow t\bar{b}}$, %	σ_{tot} , pb	$\sigma_{u\bar{d}(\bar{d}u) \rightarrow t\bar{b}}$, %
600	37.3	8.65	90.3	40.6	90.0
800	16.1	12.6	90.9	18.2	90.5
1000	9.42	14.1	90.2	10.7	91.0
5000	4.91	1.00	85.5	4.96	85.5

In Tables 2, 3 the total cross section of the process $p\bar{p}(pp) \rightarrow W/W' \rightarrow t\bar{b}$, the contribution of the interference term (in %) and the contribution of the leading subprocess $u\bar{d} \rightarrow W/W' \rightarrow t\bar{b}$ to the total cross section are listed as a function of W' masses. The tables show that the contribution from subleading subprocesses is small for all values of W' mass. The cross sections for the purely left-handed interacting W' are smaller than for the right-handed one. This difference reflects the fact of negative contribution of the interference between the left-handed interacting W' and the SM W -boson which is absent in the right-handed case. One can see that for the Tevatron (Table 2) the interference term achieves a maximum about 33.4% of the total cross section at $M_{W'}$ equal to 800 GeV, and about 14% for the LHC (Table 3) at 1 TeV W' boson mass.

To illustrate the interference between the W' and the SM W bosons in more detail Figs. 1 and 2 show the differential cross section for the s -channel single-top quark production as a function of the invariant mass of $t\bar{b}$ -system for three sets of W' masses 600 (upper plot), 800 (middle plot), and 1000 GeV (lower plot). For each value of W' masses the cases with purely left-handed and right-handed interactions of W' are plotted comparing to the SM process. All curves start from the reaction threshold at about $M_{t\bar{b}} \approx 180$ GeV. In case of right-handed interactions of W' there is no interference, and the curve for the invariant mass distribution is the algebraic sum of two independent falling down SM W and the resonant W' distributions. The picture is significantly different in case of left-handed interacting W' where in addition to the resonance pike there is an area with a minimum due to destructive interference between the SM W and the W' boson contributions. This local minimum follows

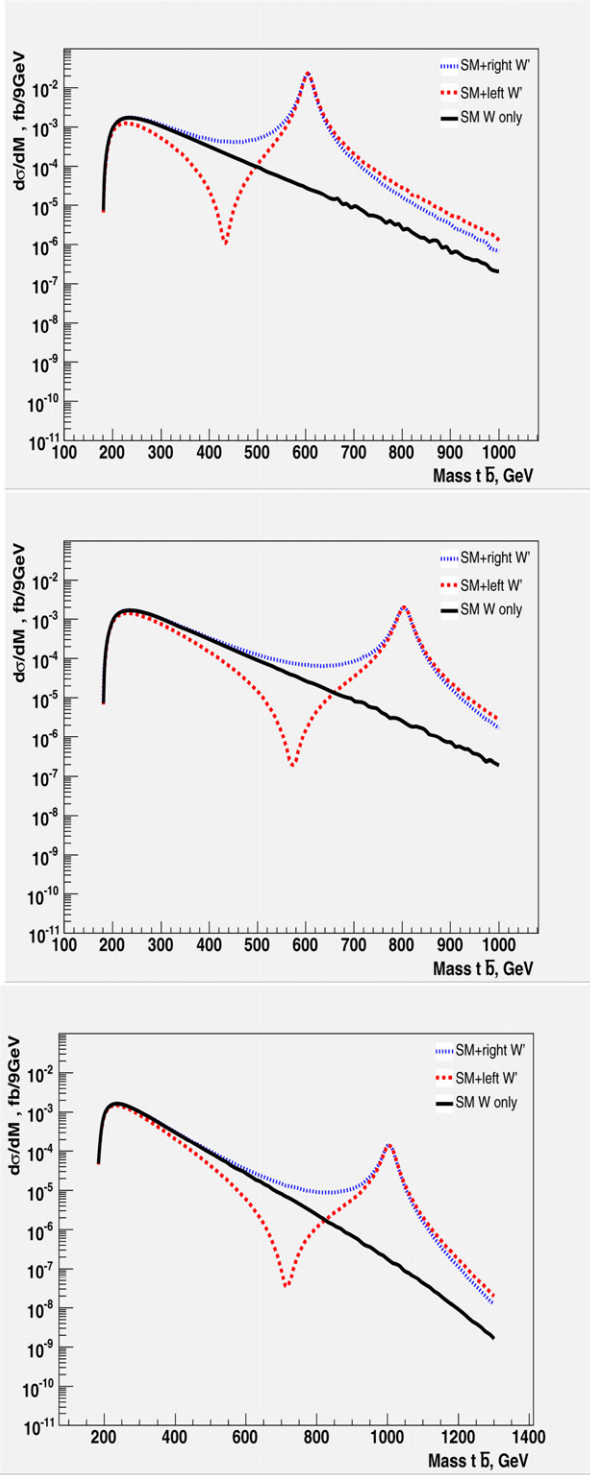


Fig. 1. Invariant mass of $t\bar{b}$ system for $M_{W'}$ equal 600, 800 and 1000 GeV respectively at the Tevatron.

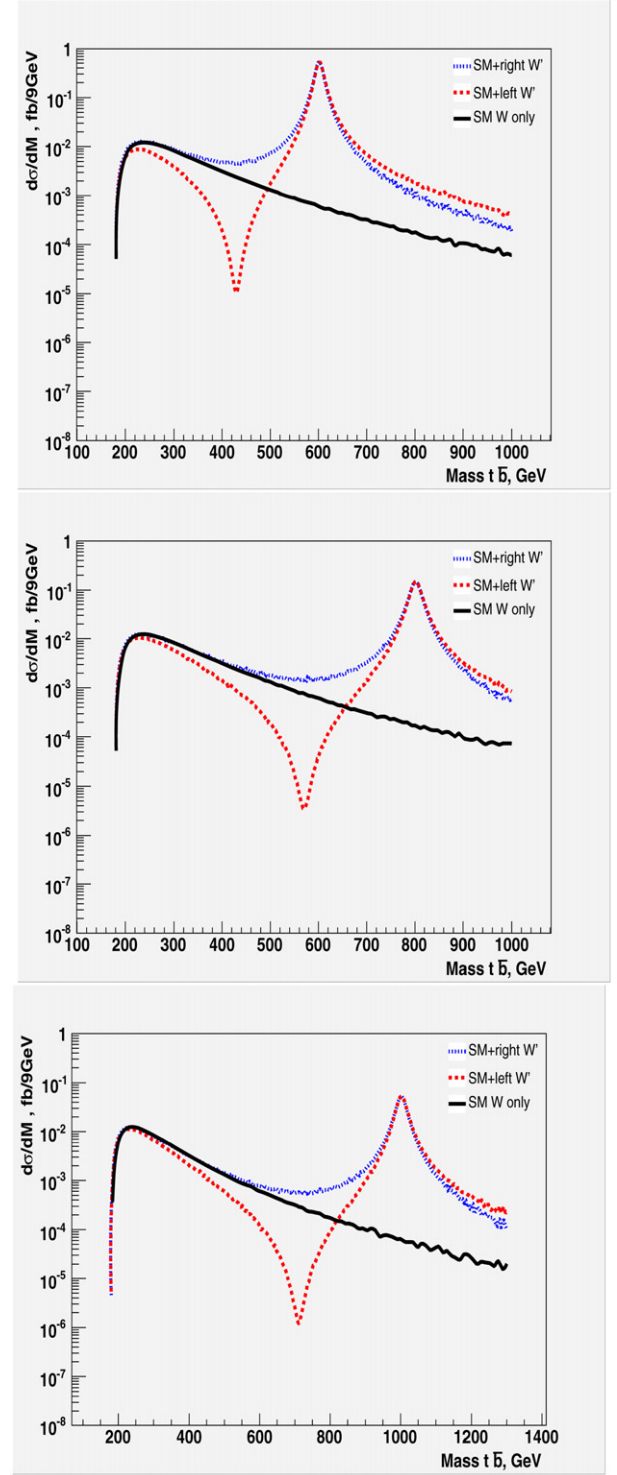
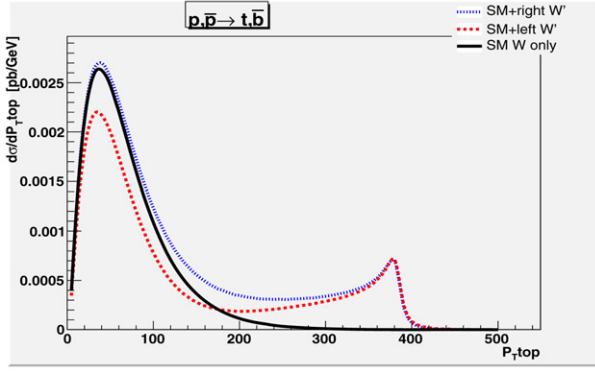
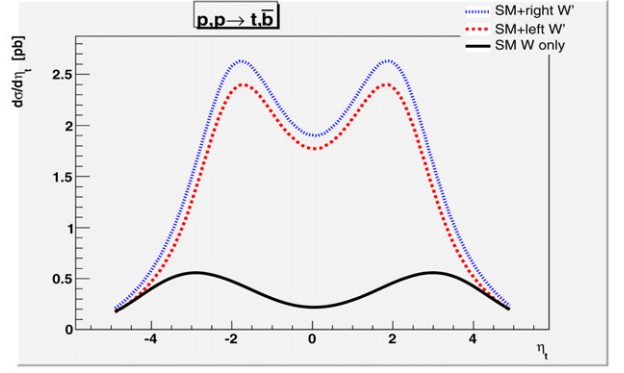
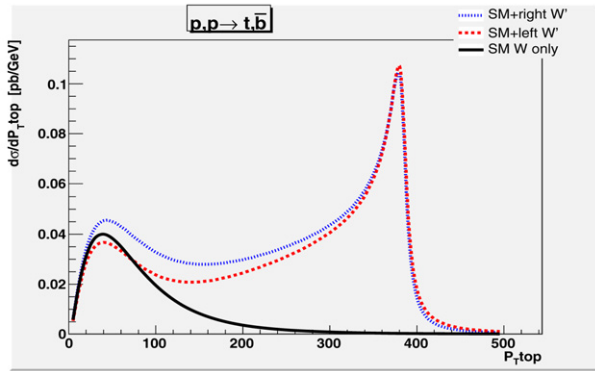
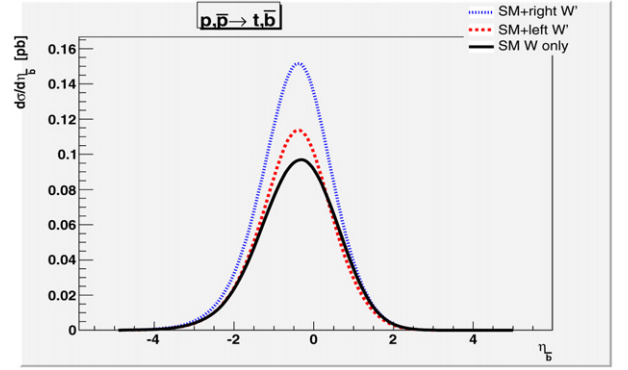
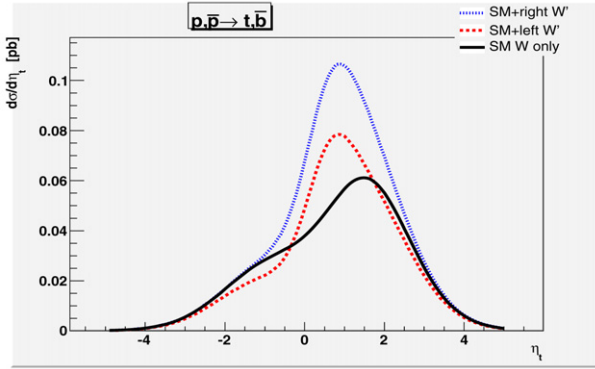
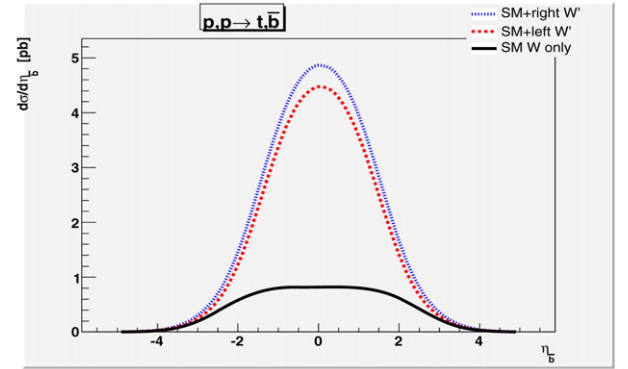


Fig. 2. Invariant mass of $t\bar{b}$ system for $M_{W'}$ equal 600, 800 and 1000 GeV respectively at the LHC.

form the formula (4) and takes place at the value of $t\bar{b}$ invariant mass $M_{t\bar{b}} = \sqrt{(M_{W'}^2 + M_W^2)/2}$.

Figs. 3–6 and 7–8 present a momentum transfer (P_T) and pseudorapidity (η) distributions of the t - and \bar{b} -quarks produced at the Tevatron and LHC. These plots once more illustrate the points discussed above. In case of SM + right interacting W'

the plot of top-quark P_T (Fig. 3) represents an algebraic sum of two distributions coming from SM W and from W' . The situation is changed in case of SM + left interacting W' , where the presence of the interference leads to a reduction of the cross section, and correspondingly the curve for this case lies below the curve for the case SM + right interacting W' . The picture for

Fig. 3. Top quark transverse momentum P_T^t (Tevatron).Fig. 6. Top quark pseudorapidity η^t (LHC).Fig. 4. Top quark transverse momentum P_T^t (LHC).Fig. 7. \bar{b} quark pseudorapidity $\eta^{\bar{b}}$ (Tevatron).Fig. 5. Top quark pseudorapidity η^t (Tevatron).Fig. 8. \bar{b} quark pseudorapidity $\eta^{\bar{b}}$ (LHC).

the LHC (Fig. 4) differs from the Tevatron case only by larger relative contribution of the W' boson decaying to the top quark. Pseudorapidity distributions of the top quark in Figs. 5, 6 also demonstrate a reduction of the rate for the case of SM + left interacting W' in comparison to the SM + right interacting W' . In contrast to the LHC (Fig. 6) the Tevatron distribution shown for the top quark only (Fig. 5) is asymmetric because of the difference in PDF for the proton and antiproton. The plots for the b -quark P_T represent distributions similar (equivalent for ideally reconstructed top decay products) with those for the top quark, but the pseudorapidity distributions of b -quarks are more central (Figs. 7, 8) comparing to the top quark.

We have simulated the complete chain of top quark decays taking into account all the spin correlations between top quark production and its subsequent decay. The separate study of angular correlations for these processes is given in the paper [36].

4. Conclusion

In this Letter we focus our attention on the interference of SM W gauge boson with a hypothetical W' vector boson in single-top production process at hadron collider. Simple symbolic formula for matrix element squared of the leading subprocess shows explicitly in a model independent way a parameter dependence for general left- and right-handed couplings.

plings of W' boson to the SM fermions. As expected a maximal influence of the interference term takes place for the case of left-handed interactions of W' . Such a destructive interference may approach as large as 30% for the Tevatron leading to a local minimum in the invariant mass distribution at $M_{tb} = \sqrt{(M_{W'}^2 + M_W^2)/2}$ and being very small close to the resonance position in tb invariant mass. The NLO corrections have been computed separately for the SM single top s -channel process [34] (background for W') and for the W' contribution [33]. Such an approach works perfectly for the case of purely right-handed interacting W' . However a recipe how to proceed from the right-handed to a general coupling case by multiplying the answer by the coefficient $a_{ud}^L a_{tb}^L + a_{ud}^R a_{tb}^R$ obviously does not work because the interference contribution and the additional term in W' contribution are proportional to different coupling combinations, the first to $a_{ud}^L a_{tb}^L$ and the second $a_{ud}^L a_{tb}^R + a_{ud}^R a_{tb}^L$ (see formulas (3), (4)). As follows from formulas (3), (4) in order to simulate the general coupling dependence one should perform the simulations for three cases, purely right-handed ($a_{tb}^R = a_{ud}^R = 1$, others equal to 0), purely left-handed ($a_{tb}^L = a_{ud}^L = 1$, others equal to 0), and mixed (for example, $a_{tb}^R = 1$, $a_{ud}^L = 1$, others equal to 0). Computation of the NLO corrections in general case including non-trivial interference remains to be done, however in a number of cases the NLO corrections can be extracted from the existing computations.

The interference contribution is important in general and has to be taken into account in searches for W' bosons performing MC event generation. Calculations described in this Letter and correspondingly created Monte Carlo event generator have been used in recent experimental searches for W' by the DØ Collaboration [37]. The special study of angular correlations in the production and decay of W' is described in the separate paper [36].

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